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Quality Factor Measurements at NTF

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I. Introduction

The dose equivalent rate in the radiation field outside of the polydoor at the Neutron Therapy Facility[1] (see Figure 1.) has been measured, using a Chipmunk, assuming a quality factor (QF) of 5, to be 25 mrem/hr. This kind of dose rate if true introduced occupancy restrictions and NTF is operating under an exemption. Based on the previous CR-39 studies[2] of the neutron field around NTF,and the amount of shielding around the NTF, it was difficult to believe that a significant neutron field exists in this area, and contributes to the measured dose rate. If the field was mostly due to gamma rays the QF setting on the Chipmunk could be reliably set to a value of one. One method of obtaining a qualitative understanding of the relative abundance of neutron and gamma contribution to the absorbed doses, is to measure the quality factor for the field. This was determined using a recombination chamber.

The recombination chamber is a gas filled ion chamber that can measure the average quality factor of a radiation field of unknown composition and energy spectrum[3,4]. The response of the recombination chamber can be described[5] as a function of the bias across it's plates as

$$I = kV^{n}, \qquad (1)$$

where I is the normalized current collected by the chamber, k is a constant of proportionality, V is the applied bias and the exponent n can be related to the quality factor of the field. To use the recombination chamber in an unknown field, one needs to have measured a calibration curve using radiation fields of known quality factor[6,7,8].

The individual neutron and gamma components of the radiation field were also determined in these studies by use of an Andersson-Braun counter (SNOOPY[9]) to measure the dose equivalent rate due to neutrons, and a CutiePie[10] ion chamber to measure the gamma dose rate. The neutron dose equivalent rate in this area of NTF has been estimated by Vylet[11,2], and is consistent with the present measurements.

II. Calibration of the Recombination Chamber

A schematic drawing of the recombination chamber setup is shown in Figure 2. The calibration was performed at the neutron irradiation area of the Radiation Physics Calibration Facility (RPCF). The recombination chamber was placed on an aluminum ladder, half way between the ceiling and floor, to minimize the effects of room scattering. Radiation with at least two different known quality factors need to be measured to produce the linear calibration curve. A gamma ray source (^{60}Co; 60-4.3-2), and a mixed neutron-gamma source (^{241}Am-Be; 241Be-7.2-1) were used to obtain the calibration reference points. The *standard* quality factor for gamma rays (of any energy) is assumed to be one. The quality factor due to neutrons is a sensitive function of energy[12]. The average quality factor for the mixed ^{241}AmBe source was calculated to be 6.6 using

$$QF = \sum_{i=1}^{n} \frac{(Dose)_i}{Total\ Dose} (QF)_i, \qquad (2)$$

where $(Dose)_i$, and $(QF)_i$ are dose and the quality factor due to the ith component of the field. Only neutron and gamma radiation fields are of interest in this note. The quality factor for the predominant neutron component of the AmBe source was taken to be 7.9[12]. The results of the calibration measurements are given in Tables I and II. The last column in each table shows the response of the recombination chamber to the radiation field which is calculated using

$$Response = \frac{I_V}{I_{saturation}}, \qquad (3)$$

where I_V is the measured current at a bias setting of V, and $I_{saturation}$ is the measured current at saturation bias which is taken as -1200 volts. The data columns labeled Data#1, Data#2, and Data#3 are one minute charge integrations and the net charge for each interval is

$$Q1(nCoulombs) = Data\#2 - Data\#1, \qquad (4)$$
$$Q2(nCoulombs) = Data\#3 - Data\#2. \qquad (5)$$

The recombination chamber response for cobalt and AmBe sources, at different bias settings are plotted in Figures 3 and 4. The power law fit with the fit parameters are also displayed on each plot. Figure 5 shows the exponent n (defined in Equation 1) plotted against the quality factor for the two sources. The linear fit to these two points, as shown on the plot, provides the calibration curve for the recombination chamber. It is in good agreement with previous calibration measurements[7]. The quality factor for any unknown field is obtained by measuring the response curve. From the fit of the response to Equation 1, the exponent n can be obtained, and the quality factor for the unknown field can be read off the calibration curve Figure 5.

III. Measurements

The main part of the measurements was done with the recombination chamber positioned at the geometric center of the polydoor at NTF, and the Chipmunk detector located on the floor outside the polydoor. The Chipmunk detector was used to provide a redundant dose normalization factor. As mentioned a SNOOPY detector was used to measure the neutron dose equivalent rate, and a CutiePie detector was used to extract the gamma ray component of the field.

To simulate the worst case operation of NTF, a large (24X24 cm^2) collimator was used, and the beam was scattered off a 5 gallon carboy containing water. Each run lasted about 2.3 minutes and delivered 0.65 monitor units.*

III.A RF and X-ray Backgrounds

A large RF background can inundate the recombination chamber and make the measurements useless. The RF levels in the area around NTF have been surveyed in the past[13], using an RF meter. However, that measurement was only concerned with the health hazards, and the qualitative conclusion was that the levels were below the health hazard threshold. We measured the background using the recombination chamber to see if there were any X-ray and RF pickup effects. This was done a day before the actual measurements and the neutron beam had been off for at least a day. The recombination chamber was operated at the recombination voltage (-65V) and the saturation voltage (-1200V) and also with and without a Faraday cage surrounding the chamber. Our background measurements revealed three important points: First, there was no measurable RF interference. Second, the measurements showed that the background levels are the same as those measured at RPCF. Third, the background was about 0.2% of the dose rate we expected to measure with the beam on, and thus of negligible effect.

III.B Background measurements

During the day of studies, with the neutron beam off, a background measurement was performed with all the detectors used in this study. The results are shown in Table III. Later measurements with the neutron beam showed that the measured backgrounds for the CutiePie, SNOOPY, and the recombination chamber were less than 0.5% of the dose that was measured with the beam on.

After the measurements were completed the background was measured again using the Chipmunk and the recombination chamber. The results are shown in Table IV. The Chipmunk's pre- and post-irradiation backgrounds are the same, the recombination chamber measured a higher post-irradiation background due to it's sensitivity to residual induced activity.

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* The neutron beam is calibrated such that one monitor unit delivers to tissue (or its equivalent) one Gray at a depth of 10cm when a 10X10 cm^2 collimator is used.

III.C Beam-On Measurements

During the beam-on measurements the polydoor was surveyed with a CutiePie; the exposure rate was highest in the middle of the door (4 - 6 mR/hr**). A dose integration was done with the CutiePie, SNOOPY and a Chipmunk at the middle of the door and on the floor . The results of these measurements are given in Tables V and VI. Data from Radiation Physics Note 86[14], and additional tests[15] show that the CutiePie has an efficiency of 100% for the gamma rays, and about 23% for the detection of neutrons. Actually the neutron detection efficiency of the CutiePie increases with energy and 23% is a conservative estimate which is true for neutrons of average energy 4.1 MeV. The SNOOPY is sensitive to neutrons only, and measures the dose equivalent rate directly[9]. As shown in Table VI, the neutron dose equivalent on the floor is 1.5 times that at the middle of the door, but the absolute value of the neutron dose equivalent is about 20% of the gamma dose equivalent. The SNOOPY's resolving time is 1 μs. For the LINAC's 57 μs pulse width, and frequency of 15Hz, the dead time correction is 0.2% for the SNOOPY measurement at the center of the door. The correction for the dose rate on the floor is 0.35%. No corrections were applied to the data, since the SNOOPY dead time correction is performed internally.

The recombination chamber's response was measured at 17 different bias setting from -30 volts to -1200 volts, as shown in Table VII. For each one of these bias settings one run was integrated. During these measurements the Chipmunk was placed on the floor and simultaneously integrated the runs, using a scaler. The Chipmunk's measurements indicated the LINAC delivered a fixed dose each run corresponding to the same number of protons. It is seen from the data that the dose delivered was very stable, and the small variation in the chipmunk count-rate (±2 counts/run) was due to variation in the background and the reaction time in manually starting and stopping the scaler.

IV. Analysis of Data

A direct way to calculate the quality factor for a radiation field is to measure the dose rate of the individual components of the field, and calculate the composite quality factor using equation 2, rewritten here as:

$$QF = \frac{D_\gamma}{D_\gamma + D_n} QF_\gamma + \frac{D_n}{D_\gamma + D_n} QF_n \qquad (4)$$

where D_γ and D_n are the gamma and neutron absorbed dose rates. QF_γ is 1.0 by convention and QF_n is determined by measuring the mean energy of the neutrons outside the polydoor at NTF. Previous measurements[11] showed the neutron spectrum peaks at 150 keV. The quality factor of 150 keV neutrons is 8.5 as shown[4] in Figure 6. The dose rate measured by the CutiePie can be described by

$$D_{CutiePie} = D_\gamma \times \varepsilon_\gamma + D_n \times \varepsilon_n \qquad (5)$$

from which we can obtain D_γ. The detection efficiencies ε_γ and ε_n are 1.0 and 0.23, respectively. From Table V we can obtain $D_{CutiePie}$, which is 0.1579 mrad/run in the middle of the door and 0.1535 mrad/run on the floor. From Table VI, D_n is 0.0033 mrad/run in the middle of the door and 0.0049 mrad/run on the floor. Using these values in the equation 5, D_γ is calculated to be 0.1569 mrad/run in the middle of the polydoor, and 0.1520 mrad/run on the floor. Substituting these values in equation 4., we obtain a quality factor 1.2 for the middle of the door and 1.3 for the floor location.

The results of Table VIII are plotted in Figure 7. A power law fit to the points leads to a value of n=0.0123, as indicated on the figure. From the calibration curve, Figure 5, this gives a quality factor for the radiation field outside of the polydoor of QF=1, consistent with the field arising almost completely from gamma radiation.

This conclusion is verified by the CutiePie and SNOOPY results. The exposure rate measured by the CutiePie is about 0.18 mR/run (Table V) or 0.158 mrad/run while the SNOOPY registered 0.042 mrem/run (Table VI) at the same location. If one assumes, based on preliminary measurements of

** Exposure rate is expressed in milli-Roentgens/hr or mR/hr.

Vylet, that the average energy of the neutrons is about 150 keV, then the QF of the neutron field[16] is about 8.5 (Figure 6) and the measured neutron absorbed dose is 0.042/8.5=0.0049 mrad/run. Thus, the neutrons contribute only about 3% to the absorbed dose outside of the polydoor. It is entirely reasonable therefore that whenever chipmunks are used to monitor the dose equivalent in this area of NTF, QF be set to 1.

It might further be pointed out that the results based on the SNOOPY measurements which give neutron dose equivalent of 0.028 to 0.042 mrem/run are in agreement with Vylet's CR-39 film badge results at the same location. A one LINAC run every 2.3 minutes, which is the configuration used during these studies, corresponds to 26 runs/hr. The neutron dose equivalent rates then vary from about 0.7 to about 1 mrem/hr. This is slightly higher but in approximate agreement with the values shown in the table in reference 2.

The quality factor obtained in these measurements, implies - as also seen from the CutiePie and SNOOPY measurements- that the main component of the field outside the NTF polydoor is gamma rays, and a small component is consistent with 150 keV neutrons. Our previous experience with the recombination chamber give a ±5% statistical error associated with the calibration curve. Typical error associated with the recombination chamber measurements, when operated in the parallel mode, is quoted[3] to be 25%. In the absence of sufficient statistics and better calibrations and, we adopt this more conservative error, and conclude that the quality factor for the radiation field outside the polydoor of NTF is 1.0±25%.

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(16) National Council on Radiation Protection, *Protection against neutron adiation*, NCRP Report 38.

Bias	Data#1	Data#2	Data#3	Q1(nC)	Q2(nC)	Ave[Q(nC)]	Response
-30	0.0197	0.1547	0.297	0.135	0.1423	0.13865	0.7013
-40	0.0373	0.1827	0.328	0.1454	0.1453	0.14535	0.7352
-65	0.0420	0.1986	0.3541	0.1566	0.1555	0.1561	0.7893
-75	0.0628	0.2209	0.3832	0.1581	0.1623	0.1602	0.8103
-85	0.065	0.2285	0.392	0.1635	0.1635	0.1635	0.827
-100	0.0683	0.234	0.3934	0.1657	0.1594	0.16255	0.8222
-200	0.094	0.2687	0.4436	0.1747	0.1749	0.1748	0.8842
-300	0.0692	0.25	0.4288	0.1808	0.1788	0.1798	0.9095
-400	0.0682	0.2481	0.4339	0.1799	0.1858	0.18285	0.9249
-500	0.073	0.2598	0.4444	0.1868	0.1846	0.1857	0.9393
-600	0.0746	0.2653	0.4565	0.1907	0.1912	0.19095	0.9659
-700	0.071	0.2653	0.4587	0.1943	0.1934	0.19385	0.9805
-800	0.0744	0.2706	0.4627	0.1962	0.1921	0.19415	0.982
900	0.0965	0.2888	0.4874	0.1923	0.1986	0.19545	0.9886
-1000	0.0829	0.2832	0.4823	0.2003	0.1991	0.1997	1.0101
-1100	0.074	0.2718	0.4682	0.1978	0.1964	0.1971	0.997
-1200	0.1326	0.3299	0.528	0.1973	0.1981	0.1977	1

Table I. Recombination chamber calibration data with the AmBe mixed neutron and gamma source. The background for this run was measured to be 0.00087nC/min.

Bias	Data #1	Data #2	Data #3	Q1(nC)	Q2(nC)	Ave [Q(nC)]	Response
-30	0.248	1.284	2.308	1.036	1.024	1.03	0.9445
-40	0.257	1.314	2.36	1.057	1.046	1.0515	0.9642
-65	0.247	1.304	2.36	1.057	1.056	1.0565	0.9688
-75	0.315	1.373	2.433	1.058	1.06	1.059	0.9711
-85	0.271	1.34	2.393	1.069	1.053	1.061	0.9729
-100	1.743	2.818	3.878	1.075	1.06	1.0675	0.9789
-200	0.362	1.438	2.518	1.076	1.08	1.078	0.9885
-300	0.71	1.797	2.872	1.087	1.075	1.081	0.9913
-400	0.826	1.9	2.992	1.074	1.092	1.083	0.9931
-500	0.358	1.446	2.537	1.088	1.091	1.0895	0.9991
-600	1.182	2.261	3.355	1.079	1.094	1.0865	0.9963
-700	2.138	3.224	4.314	1.086	1.09	1.088	0.9977
-800	0.48	1.572	2.661	1.092	1.089	1.0905	1.0000
900	1.519	2.611	3.701	1.092	1.09	1.091	1.0005
-1000	2.415	3.497	4.59	1.082	1.093	1.0875	0.9972
-1100	0.644	1.743	2.824	1.099	1.081	1.09	0.9995
-1200	0.444	1.535	2.625	1.091	1.09	1.0905	1.0000

Table II. Recombination chamber calibration data with the ^{60}Co source. The background for this run was measured to be 0.00087nC/min.

Instrument	Location	Time(min)	Reading	Units
Cutie Pie	Center of Door	10.	0.001	mR
Chipmunk	Center of Door	10.	49	counts
SNOOPY	Floor	10.	2.34E-4	mrem
Chipmunk	floor	10.	48	counts
Rec. Cham. (-65V)	Center of Door	10.	-33E-4	nCoul.
Rec. Cham. (-1200V)	Center of Door	10.	-39E-4	nCoul.
SNOOPY	Center of Door	10.	1.17E-4	mrem

Table III. Background measurements outside the polydoor.

Instrument	Location	Time(min)	Reading	Units
Chipmunk	Floor	10.	46	counts
Rec. Cham. (-65V)	Center of Door	10.	-0.0155	nCoul.
Chipmunk	Floor	10.	47	counts
Rec. Cham. (-1200V)	Center of Door	10.	-0.0156	nCoul.

Table IV. Post irradiation background measurements outside the polydoor at NTF.

Location	Dose(mR/run)
Center of Door	0.18
Floor	0.175

Table V. CutiePie dose integration outside the polydoor.

Monitor (Dose)	Chipmunk Location	Counts (gross)	SNOOPY Location	Dose (mrem)
0.62 Gy	Center of Door	422	Floor	4.24E-2
0.62 Gy	Floor	274	Center of Door	2.81E-2

Table VI: Simultaneous dose measurements with Chipmunk and SNOOPY. Each measurement is a one-run integration.

Recombination	Chamber	Chip munk	
(Volts)	(nCoul.)	Counts	Time(sec)
-30	0.5360	274	223
-40	0.5422	274	248
-65	0.5463	272	217
-75	0.5481	271	217
-85	0.5503	270	210
-100	0.5526	274	251
-200	0.5591	274	250
-300	0.5603	276	243
-400	0.5610	276	248
-500	0.5606	275	258
-600	0.5622	274	252
-700	0.5657	275	250
-800	0.5654	275	251
-900	0.5640	276	252
-1000	0.5646	273	252
-1100	0.5651	276	253
-1200	0.5641	274	254
-800	0.5622	---	---
-85	0.5499	276	252
-65	0.5495	274	250

Table VII: Simultaneous dose measurements with recombination chamber and Chipmunk. Each measurement is a one-run integration.

Bias	Data #1	Data #2	Q1(nC)	Response
-30	0.0011	0.5371	0.536	0.9502
-40	0.0003	0.5425	0.5422	0.9612
-65	0.0002	0.5465	0.5463	0.9684
-75	0.0019	0.5506	0.5487	0.9727
-85	0.0012	0.5515	0.5503	0.9755
-100	0.0018	0.5544	0.5526	0.9796
-200	0.0025	0.5616	0.5591	0.9911
-300	0.0018	0.5621	0.5603	0.9933
-400	0.0006	0.5616	0.561	0.9945
-500	0.0064	0.567	0.5606	0.9938
-600	0.003	0.5652	0.5622	0.9966
-700	0.0036	0.5693	0.5657	1.0028
-800	0.0011	0.5665	0.5654	1.0023
-900	0.004	0.568	0.564	0.9998
-1000	0.0027	0.5673	0.5646	1.0009
-1100	0.0035	0.5686	0.5651	1.0018
-1200	0.0013	0.5654	0.5641	1.0000
-800	0.0039	0.5661	0.5622	0.9966
-85	0.0026	0.5525	0.5499	0.9748
-65	0.0038	0.5533	0.5495	0.9741

Table VIII. Recombination chamber data and response from the NTF measurements.

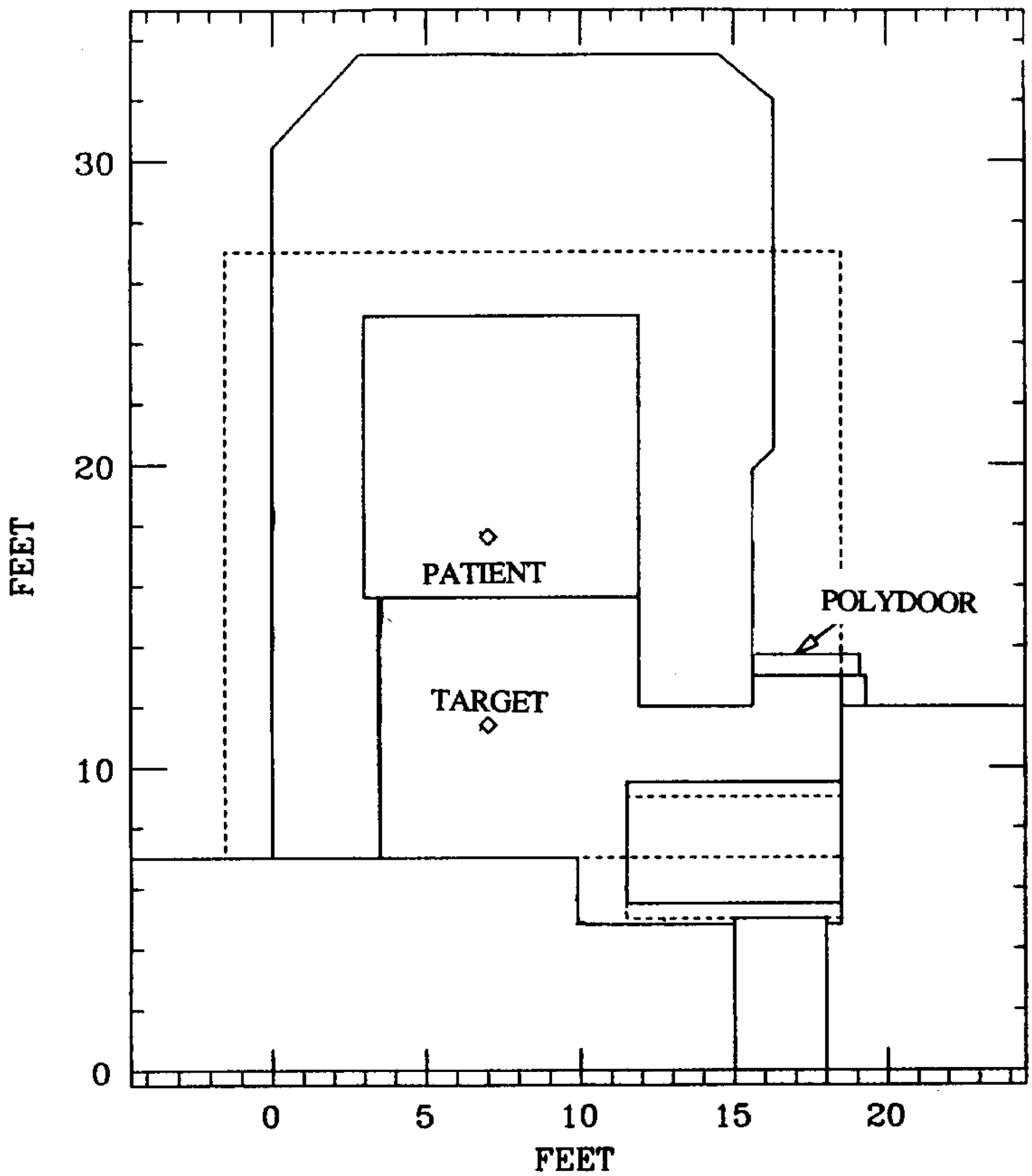

Figure 1. Layout of the NTF. The neutron production target and the treatment room where the phantom was located are below the ground floor and the polydoor was located on the ground floor.

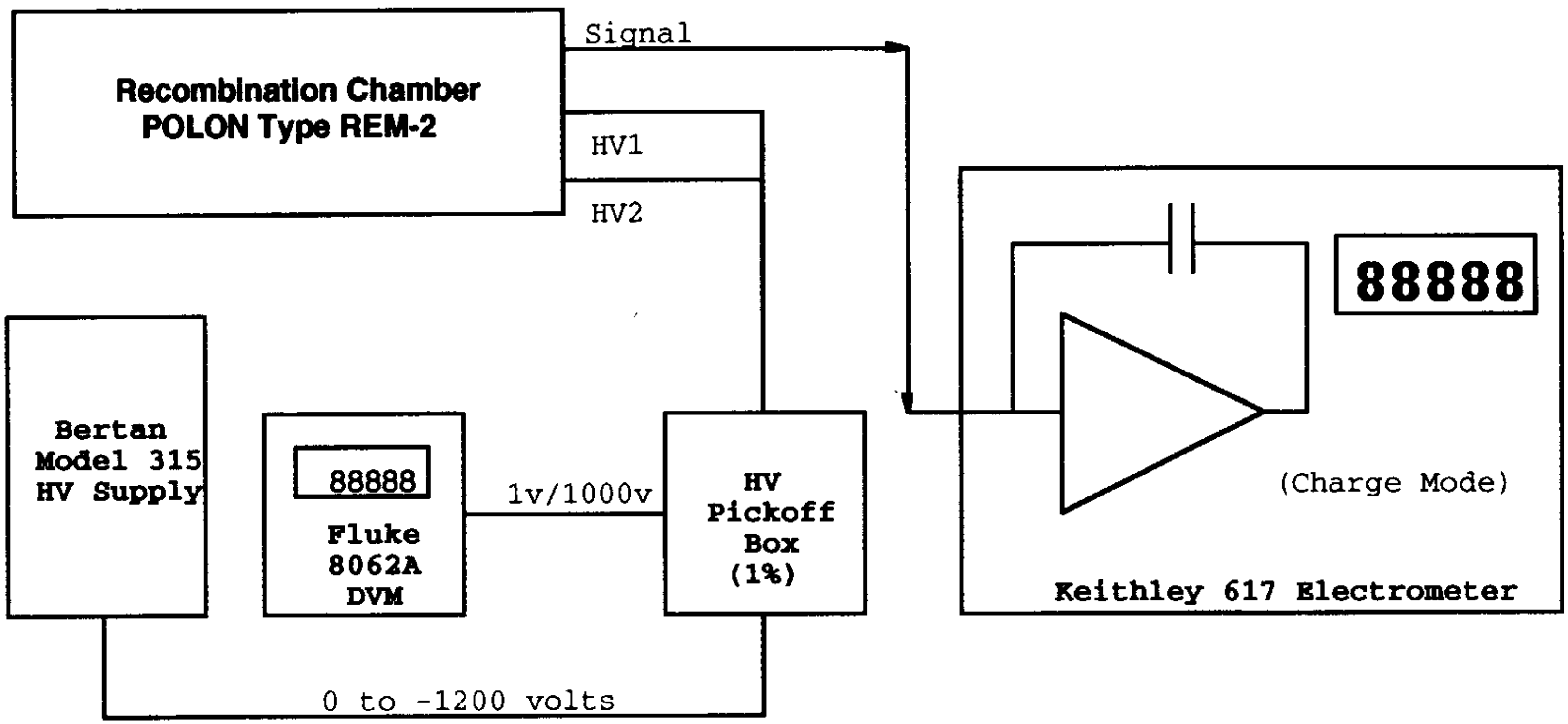

Figure 2. Schematic diagram of the recombination chamber setup for quality factor measurements.

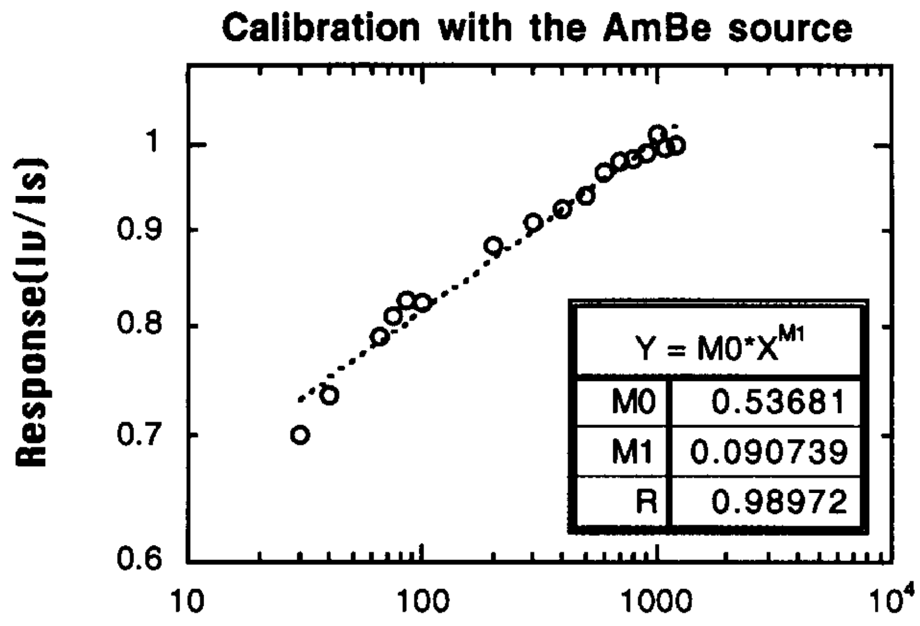

Figure 3. Response of the recombination chamber as a function of its bias settings to the AmBe source.

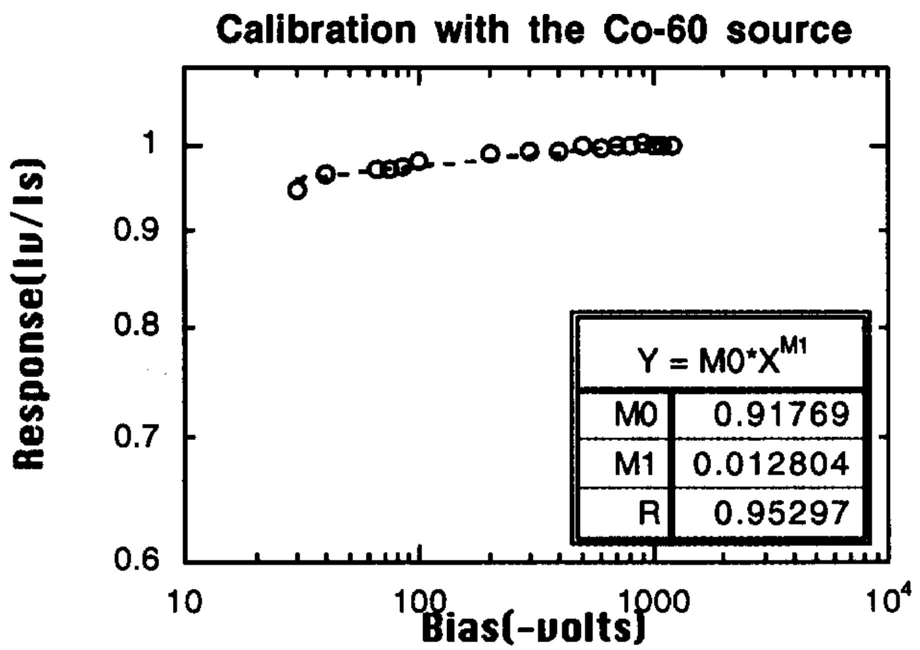

Figure 4. Response of the recombination chamber as a function of its bias settings to the ^{60}Co source.

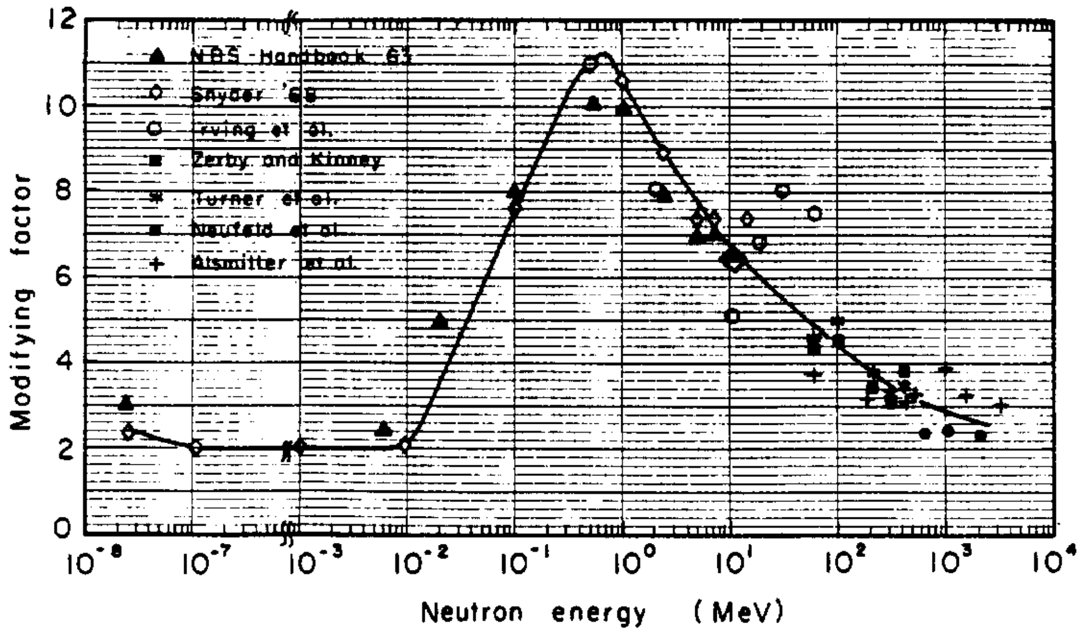

Figure 6. Neutron quality factor as a function of neutron energy.

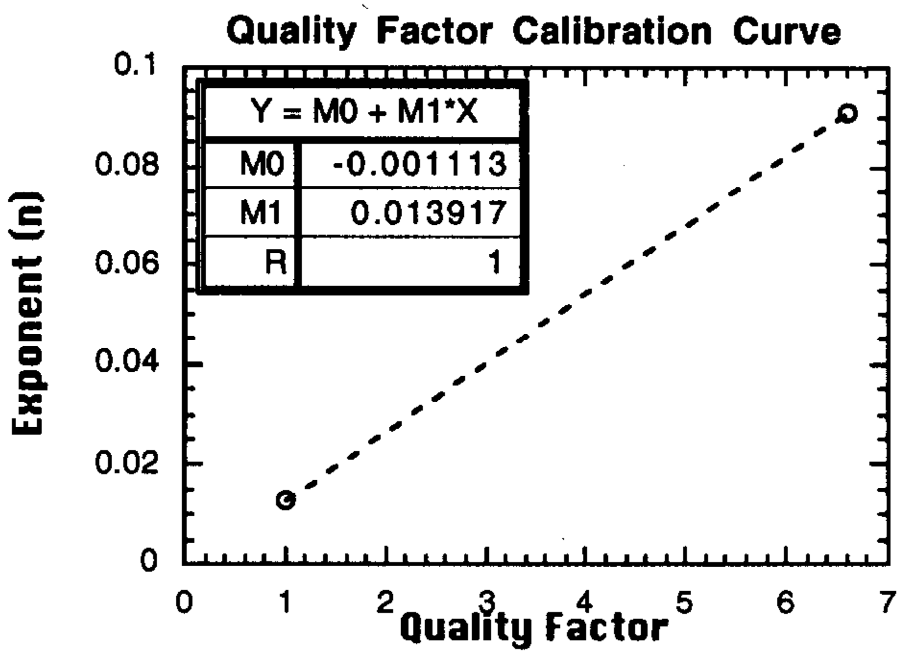

Figure 5. Calibration curve for the recombination chamber.

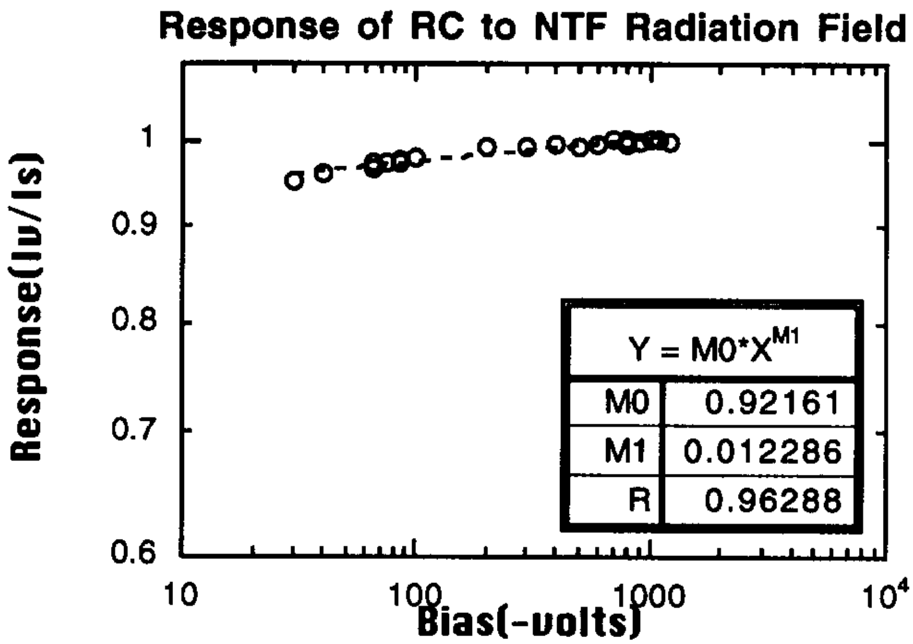

Figure 7. Response of the recombination chamber as a function of its bias settings in the NTF radiation field.